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(PERIOD ENDING SEPTEMBER 25, 1967)  
FOR  
APPLIED RESEARCH AND FEASIBILITY STUD-  
IES, EXPERIMENTAL INVESTIGATIONS AND  
CONCEPTUAL OR PRELIMINARY DESIGN ENG-  
INEERING APPLICABLE TO INVERTERS FOR  
MOTORS PROGRAM.

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## ABSTRACT

This is the First Quarterly Progress Report for Engineered Magnetics' Applied Research and Feasibility Studies, Experimental Investigations, And Conceptual Or Preliminary Design Engineering Applicable To Inverters For Motors. This report describes the accomplishments achieved during the period from June 22, 1967 to September 25, 1967. Information concerning motor specification, motor control, Inverter breadboard design, and Inverter breadboard fabrication and testing is presented herein.

## PREFACE

The National Aeronautics and Space Administration Contract Number NAS8-20832, Applied Research and Feasibility Studies, Experimental Investigations and Conceptual or Preliminary Design Engineering Applicable To Inverters For Motors Program, was awarded to the Engineered Magnetics Division of Gulton Industries, Inc., on June 22, 1967.

This is the First Quarterly Progress Report pertaining to the Engineered Magnetics Applied Research and Feasibility Studies of Inverters for Motors Program, presenting the progress of the program from June 22, 1967 to September 25, 1967. This report contains a review of the technical information which has guided the decisions and accomplishments for this period.

I. INTRODUCTION

This is the First Quarterly Progress Report for Engineered Magnetics' Applied Research And Feasibility Studies, Experimental Investigations, And Conceptual Or Preliminary Design Engineering Applicable To Inverters For Motors. (herein after referred to in the report body as Applied Research And Feasibility Studies Of Inverters For Motors Program.)

The authority to proceed for this study program is contained in NASA Contract No. NAS8-20832, dated June 22, 1967.

The study program objectives are to advance in the areas of design, efficiency, life expectancy, reliability, and motor performance characteristics of inverters for space vehicle application.

This study program shall endeavor to advance technology in the field of power conditioning with improved design concepts and techniques.

The Applied Research And Feasibility Studies Of Inverters For Motors Program will be based on information obtained from Engineered Magnetics Inverters For Motors Study Program conducted per NASA Contract No. NAS8-18013.

## II. WORK ACCOMPLISHED: THIS REPORT PERIOD

### A. MOTOR SPECIFICATION.

A procurement specification for a 3 phase induction motor was prepared. A 3 phase induction motor was ordered to this specification. The motor has a rating of 100 watts output and operates on an input of 400 Hz. The motor is designed with bifilar windings to permit operation with the six phase, half wave Inverter shown in Figure 1. An additional motor field housing (stator) assembly was also ordered. One stator consists of conventional iron (14 mil M-19 silicon steel), the other stator utilizes a high nickel material (Allegheney Ludlum 4750, 7 mil lamination). Motor operation with each stator will be analyzed to determine, empirically what improvement may be obtained when a material with lower core loss is used. The motor assemblies are scheduled to be delivered at Engineered Magnetics in December, 1967.

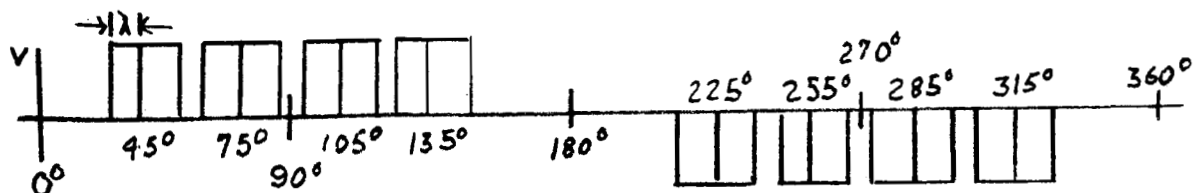
The motors procured for the Inverters For Motors Study Program (NASA Contract No. NAS8-18013) will be utilized until the 3 phase induction motor is received at Engineered Magnetics.

### B. MOTOR VOLTAGE CONTROL

Two methods of motor voltage control being considered are described below.

#### 1. Method 1.

This method consists of controlling the pulse-width modulation of the quasi-square wave voltage as it is applied to the motor. The following voltage wave-shape is evaluated.



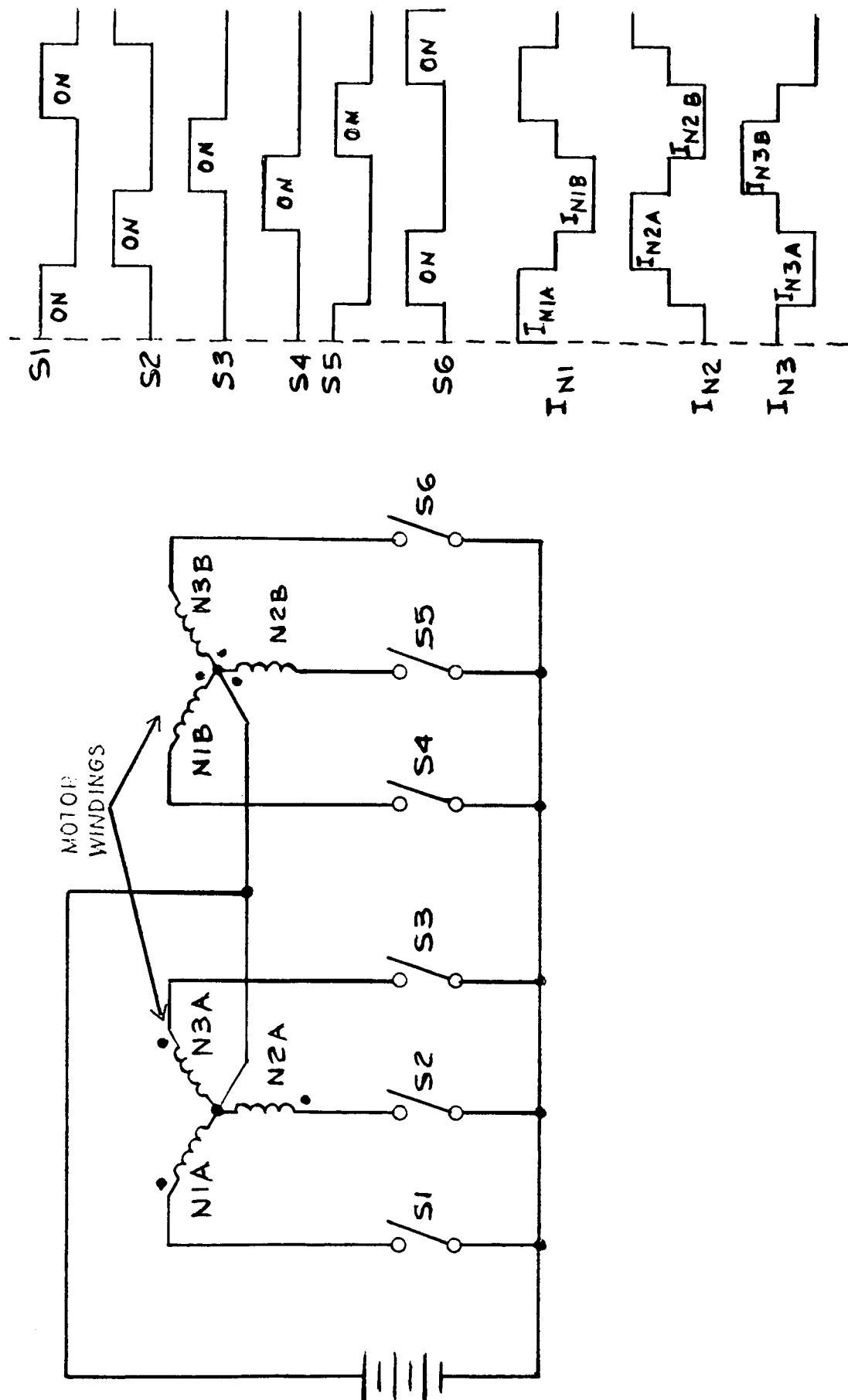


FIGURE 1. SIX PHASE HALFWAVE INVERTER WITH BIFILAR WOUND MOTOR.

The harmonic content of this waveshape is evaluated by performing a Fourier Analysis. Since the waveshape has half-wave and axis symmetry the integration is performed from  $0^\circ$  to  $90^\circ$ .

$$\text{Therefore, } e(t) = \frac{4V}{\pi} \left[ \int_{45^\circ - \lambda}^{45^\circ + \lambda} \sin nx \, dx + \int_{75^\circ - \lambda}^{75^\circ + \lambda} \sin nx \, dx \right], \quad n=1,3,5,\dots \\ 0 < \lambda \leq 15^\circ$$

$\lambda$  is as defined in the waveshape illustration.  $\frac{2\lambda}{30^\circ}$  is the on-to-off time. When  $\lambda=15^\circ$  the waveshape degenerates into the conventional quasi-square wave.

Performing the indicated integration results in

$$e(t) = \frac{-4V}{n\pi} \left[ \cos n(45^\circ + \lambda) - \cos n(45^\circ - \lambda) \right] + \frac{(-)4V}{n\pi} \left[ \cos(75^\circ + \lambda) - \cos(75^\circ - \lambda) \right].$$

By using the identity  $\cos(x \pm y) = \cos x \cos y \mp \sin x \sin y$ , the expression becomes  $e_n(t) = \frac{8V}{n\pi} (\sin n 45^\circ \sin n\lambda + \sin n 75^\circ \sin n\lambda)$ , and substituting numeral 1,3,5,--- for  $n$ , results in

$$e_1 = \frac{8V}{\pi} (.7071 \sin \lambda + .96593 \sin \lambda) = 4.26V \sin \lambda.$$

$$e_3 = 0.$$

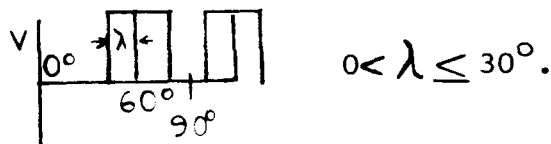
$$e_5 = 0.228V \sin 5\lambda.$$

$$e_7 = 0.163 \sin 7\lambda.$$

$$e_n = \frac{8V}{\pi} (\sin n 45^\circ + \sin n 75^\circ) \sin n\lambda.$$

These curves are shown in Figure 2.

The same procedure when applied to a two pulse per  $180^\circ$  waveshape is as shown below,



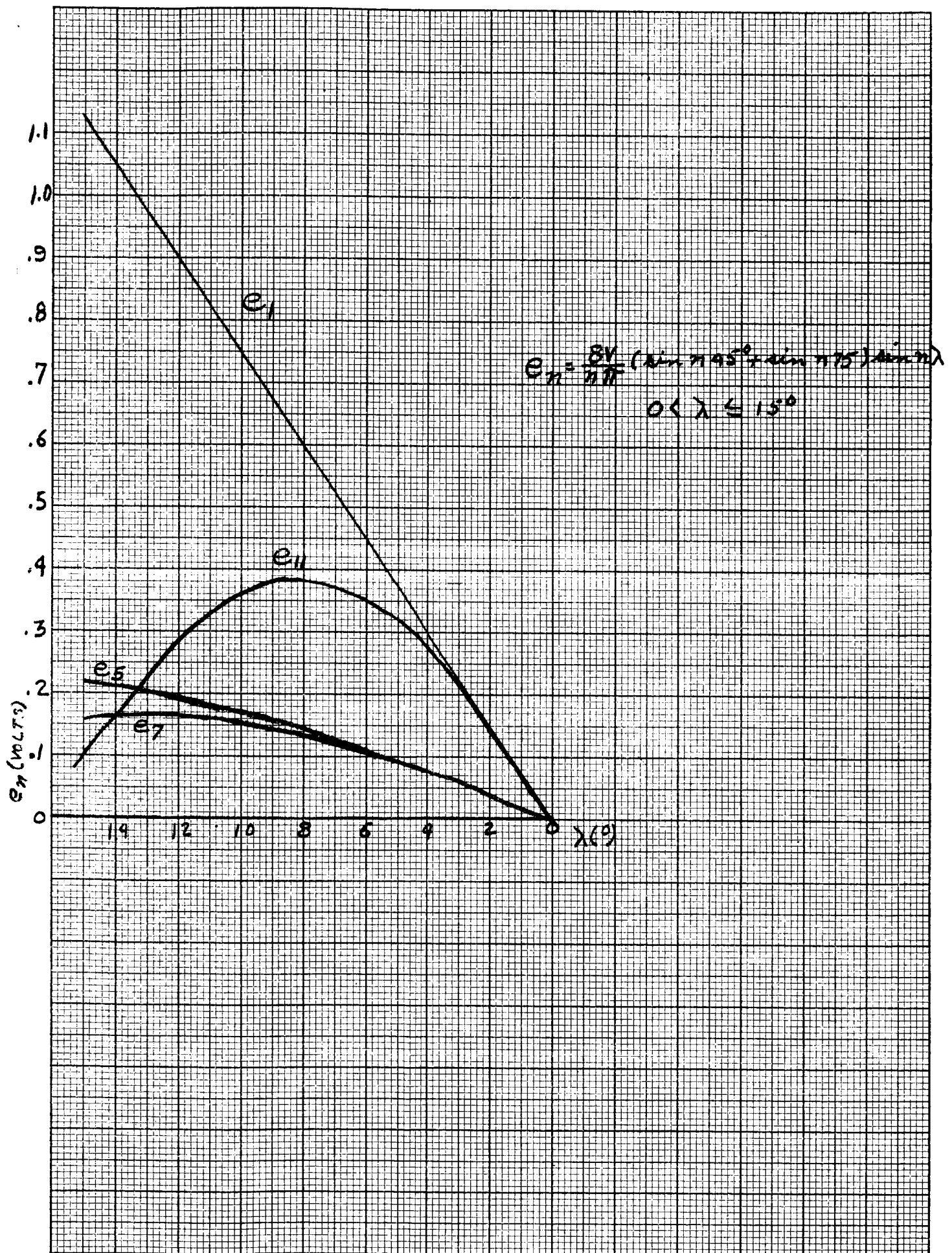


FIGURE 2. WAVESHAPE OF  $e_n$  WITH  $\lambda \leq 15^\circ$ .

This results in  $e_n = \frac{8V}{n\pi} \sin n 60^\circ \sin n\lambda$ ; then by substitution

$e_1 = 2.205 \text{ V} \sin \lambda$ ,  $e_5 = .442 \text{ V} \sin 5\lambda$ ,  $e_7 = .316 \text{ V} \sin 7\lambda$ , and  $e_{11} = 0.20 \text{ V} \sin 11\lambda$ . These curves are shown in Figure 3.

Figures 2 and 3 show that the fundamental component ( $e_1$  curve) is approximately linear with the pulse-width, and that the number of pulses-per-cycle greatly effects the amplitude of the harmonics generated. Figure 2 has fewer 5th and 7th harmonics than Figure 3, but in Figure 2 the higher harmonics have increased.

## 2. Method 2.

The other method being evaluated for controlling the voltage that is applied to the motor, is to insert a switching regulator in the power line and thus have direct control of the applied voltage.

The relative advantages of the two methods are determined by the effect of the chopped wave on motor performance.

## 3. Expanded Pulse Modulating Frequency.

The Fourier Analysis of 2 pulses per  $180^\circ$  (1/2 cycle) and 4 pulses per  $180^\circ$  was expended to include 8 pulses per  $180^\circ$ . Using the procedure described above the expression for the various harmonics becomes

$$e_n = \frac{8}{n\pi} (\sin n 37.5^\circ + \sin n 52.5^\circ + \sin n 67.5^\circ + \sin n 82.5^\circ) \sin n\lambda.$$

$$0 < \lambda \leq 7.5^\circ.$$

The curves on Figure 4 show the variations of harmonic amplitude versus lambda ( $\lambda$ ). As these curves indicate the pulse modulating frequency should be at least 24 times the line frequency.

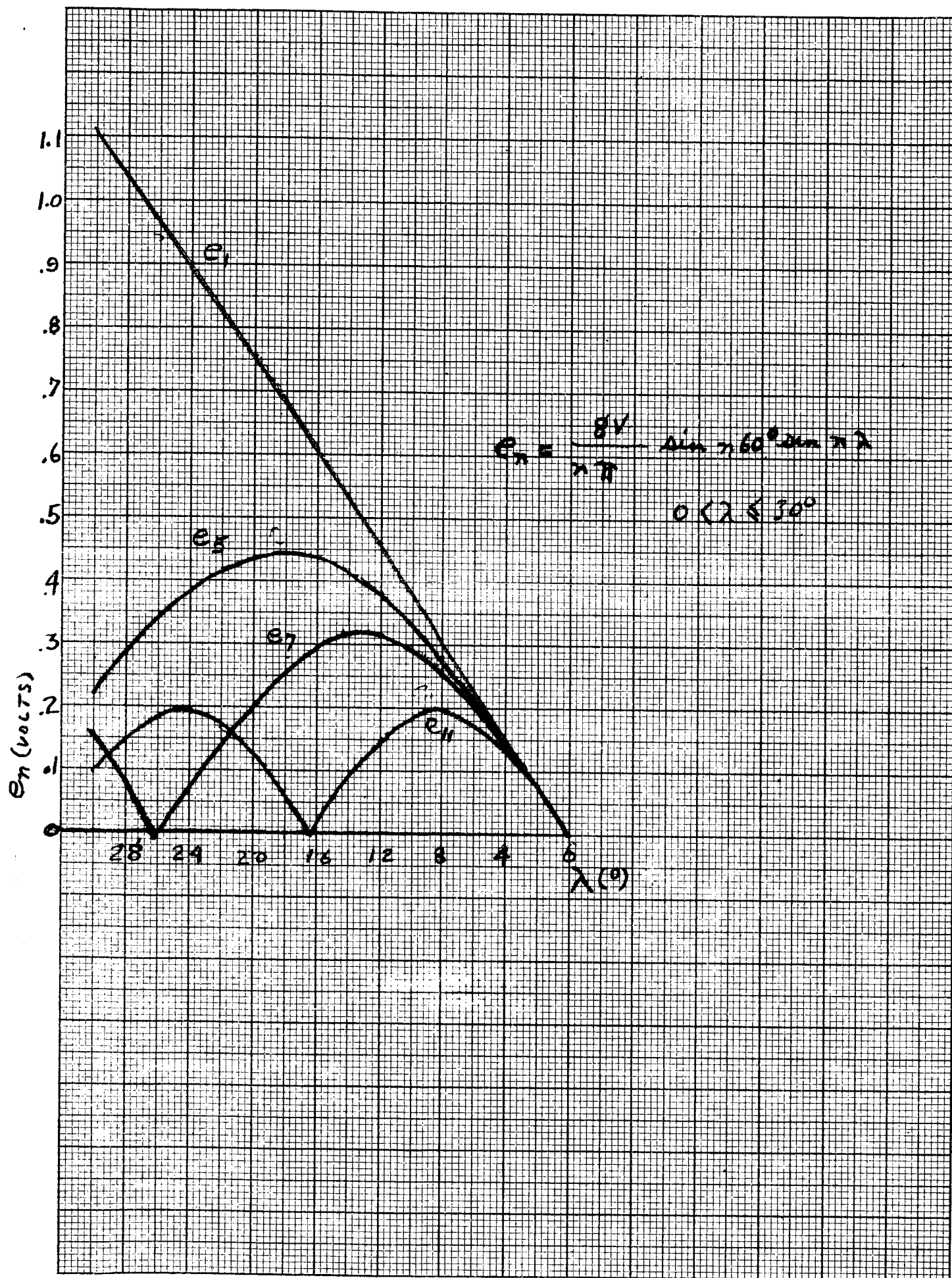


FIGURE 3. WAVESHAPE OF  $e_n$  WITH  $\lambda \leq 30^\circ$ .

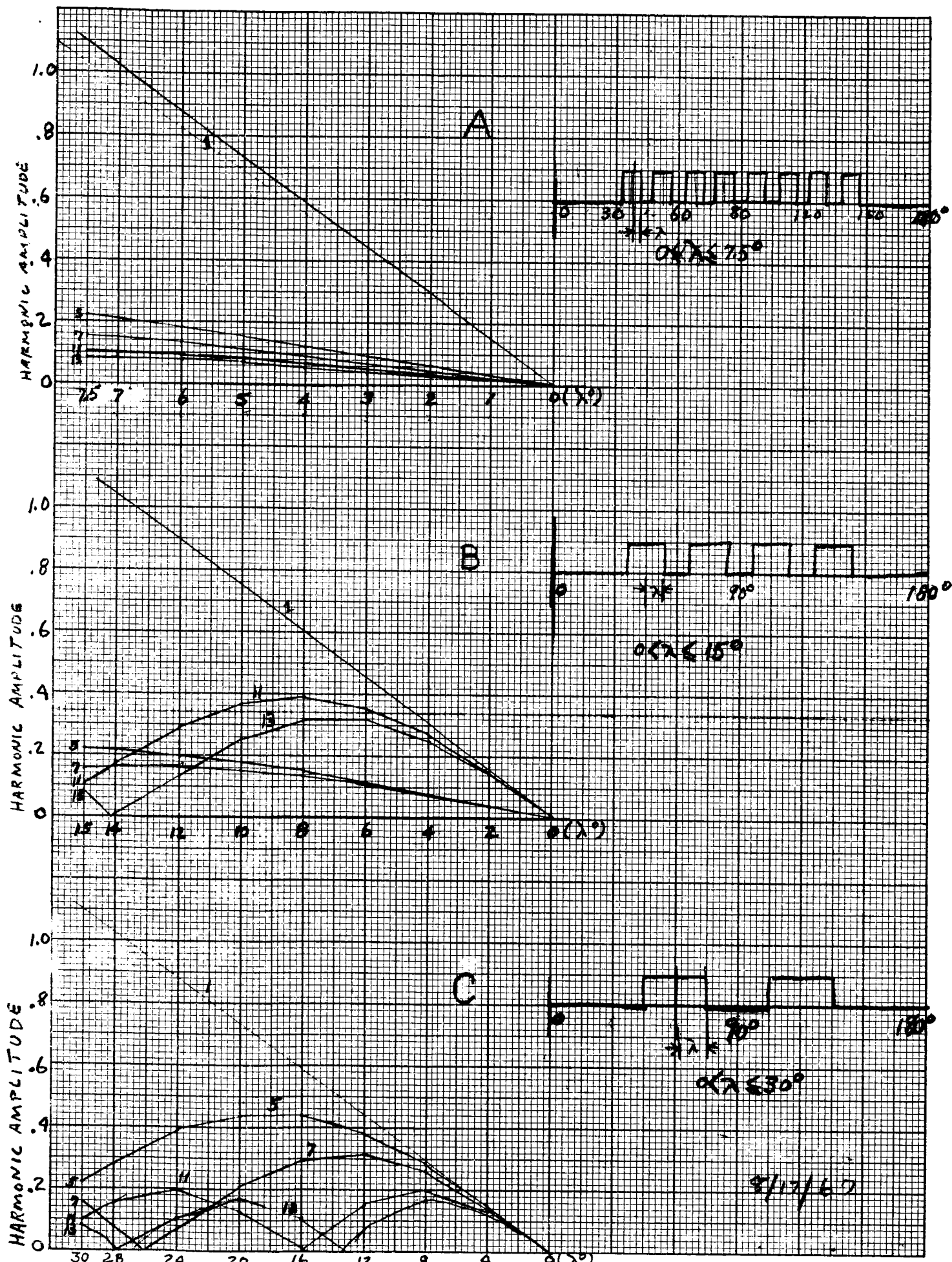


FIGURE 4. HARMONIC AMPLITUDE VS LAMDA ( $\lambda$ ).

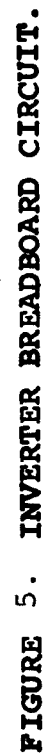
C. INVERTER BREADBOARD.

1. Inverter Breadboard Design.

An Inverter breadboard was fabricated to permit evaluation of motor-system performance at variable frequencies and pulse widths. One of the requirements of this breadboard is that no transformers are to be employed, either as output transformers or drive transformers. The engineering sketch, Figure 5, shows the Inverter and inverter gating of the ring-tailed counter for generating the 3-phase signals. Logic gating for motor reversal and pulse modulation input is also shown. This power transistor-driver arrangement was utilized to drive the presently available 3 phase motors without the use of drive transformers.

Since many different input voltages are required by the Inverter breadboard, a simple converter was built to generate the +10, +5, and +3 Volt inputs. These circuits are all referenced to ground. Additional 5 volt and 3 volt outputs are generated and referenced to the main Inverter input voltage. The diagram on Figure 6 shows the converter power supply that was built to furnish the Inverter input voltages. Note that V3 and V4 are referenced to V5. V5 is the main power input to the Inverter.

The circuits on Figure 7 are for slip control and pulse width control. In this circuit design the two monostable multi-vibrators generate pulses of approximately 150 microseconds. The diode detectors with the operational amplifier generate a voltage proportional to the difference of the input frequencies. As this is a closed loop feed-back arrangement, motor slip may be controlled by the amplifier offset control. The offset control

 $V_5 = 20-30VDC$

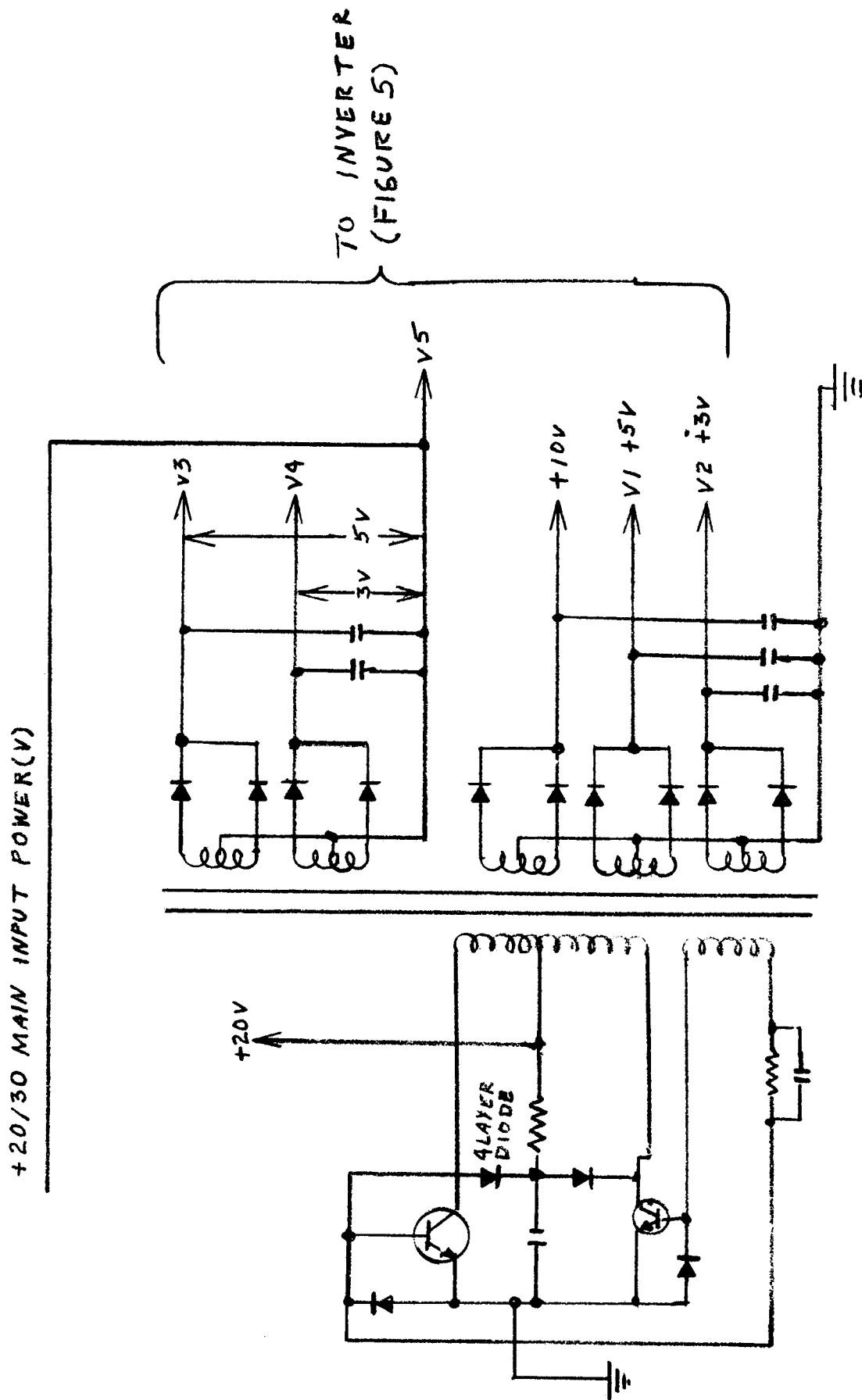


FIGURE 6. INVERTER BREADBOARD POWER SUPPLY.



voltage is applied to the differential amplifier (Q7, Q8, and Q9). In this circuit Q7 controls the charging current through C1 and the frequency of the unijunction oscillator Q6. R3 sets the minimum frequency of oscillation (Q7 is cut off), and R4 sets the maximum oscillating frequency (Q9 is cut off). The three binary dividers (FF3, 4, and 5) operate in conjunction with the pulse width control circuit (FF6, Q10, and Q11) to generate the pulses shown on Figure 4. When S3 (Figure 7) is in the down position the pulse width modulation is not synchronized to the motor frequency but is approximately 8.5 KHz.

The block diagram, Figure 8, shows the present Inverter/motor system design. This system is designed for constant slip-variable power operation. The motor input current is set by motor voltage control R5 (Figure 7). When S2 and S3 are both in the 'down' position the motor will accelerate until it is operating at a fixed slip. If the motor load is increased the slip detector circuit will sense the change in slip and will decrease the oscillator frequency. The oscillator frequency will be decreased until the motor is again running at a fixed slip and the delivered torque matches the load requirement. This system is the type required for traction drive application with R5 functioning as the vehicle accelerator control. The speed and slip control circuits can be used for any system regardless of size. If a larger motor is to be utilized, the only design change required will be in the Inverter output stages.

## 2. Inverter Breadboard Tests.

The slip control circuit was evaluated by supplying an audio frequency to the base of Q2 and then measuring the oscillator output frequency. The frequencies

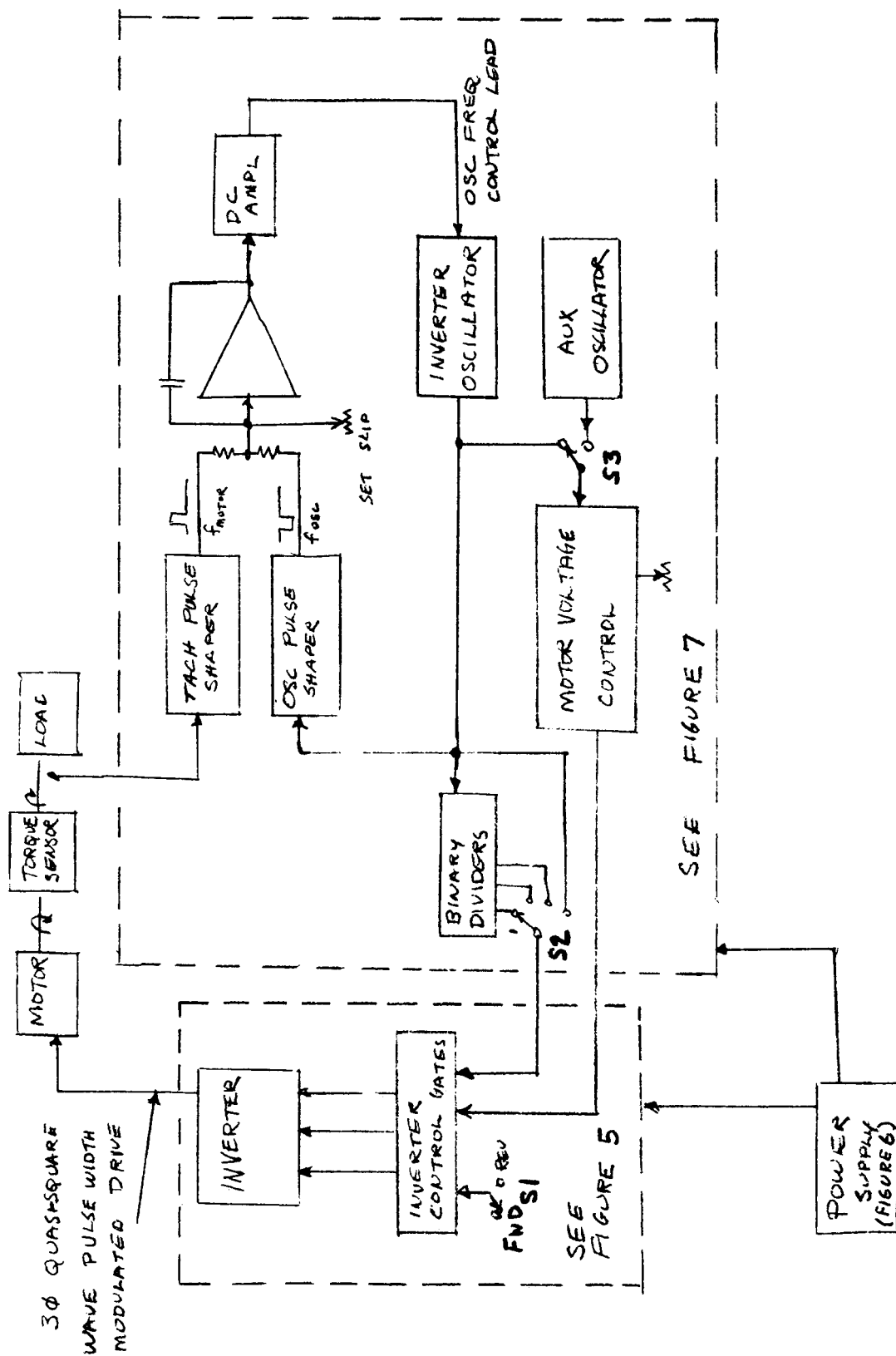


FIGURE 8. BLOCK DIAGRAM, BREADBOARD, INVERTER/MOTOR SYSTEM.

measured are 6 times the motor input line frequencies as required by the ring counter. The test results are tabulated as follows:

# SLIP CONTROL EVALUATION

$f_{\text{INPUT}}$ (Hz)	$f_{\text{OSC}}$ (Hz)	$f_{\text{MOTOR}}$ (Hz)	SLIP (Hz) (400 Hz reference)
3008	3052	509	7.3
2506	2527	423	3.5
2009	2037	339	4.65
1518	1564	261	7.7
1004	1078	180	12.3
500	606	101	17.7

The slip would remain at a more constant level if the DC loop gain were increased.

When the motor is driven by a signal similar to that shown in Figure 4 there is no torque developed until the waveform very nearly approaches a quasi-square wave. The voltage control appears to be effective when a high pulse width frequency of approximately 8.5 KHz is utilized. This lack of torque is apparently caused by the resetting of the motor core to zero during the "zero voltage" interval which occurs in the period between pulses. When the field current drops to zero, a negative current pulse is generated in the rotor circuit resulting in no net rotational torque that can be measured.

Figure 9 illustrates a transducer voltage pulse width controller that functions as a current monitor to limit the input current to a value set by R2, (the previously designed Pulse Width Control Circuit is shown as part of Figure 7.) A voltage is developed across R2 that is proportional to the main input current. The 500 turn windings of T1 and T2 support the square wave signal supplied from a winding on the converter transformer. A DC current flowing in the one turn secondaries will bias the cores so that they will saturate for part of the cycle. DC voltage developed across resistor R1 is sampled and compared with a reference voltage by emitter-coupled differential amplifier Q1 and Q2. When Q1 conducts Q3 will deliver a charging current to unijunction oscillator capacitor C2, and the oscillator will operate at a frequency which will produce the waveform shown in Figure 4. The stepped quasi-square wave, Figure 4, duty cycle ( $\lambda$ ) will be so designed that maximum current drawn by the Inverter motor combination will not exceed the value set by current control resistor R2. A minimum value of 5 amperes DC current limiting can be selected with the present circuit.

Due to several transistor failures in the Inverter section, the output transistors were changed from 2N3771 to RCA TA2669. The driver transistors were changed to a higher voltage type (2N3585). Bread-board operation with these transistors will be analyzed and discussed at a later date.

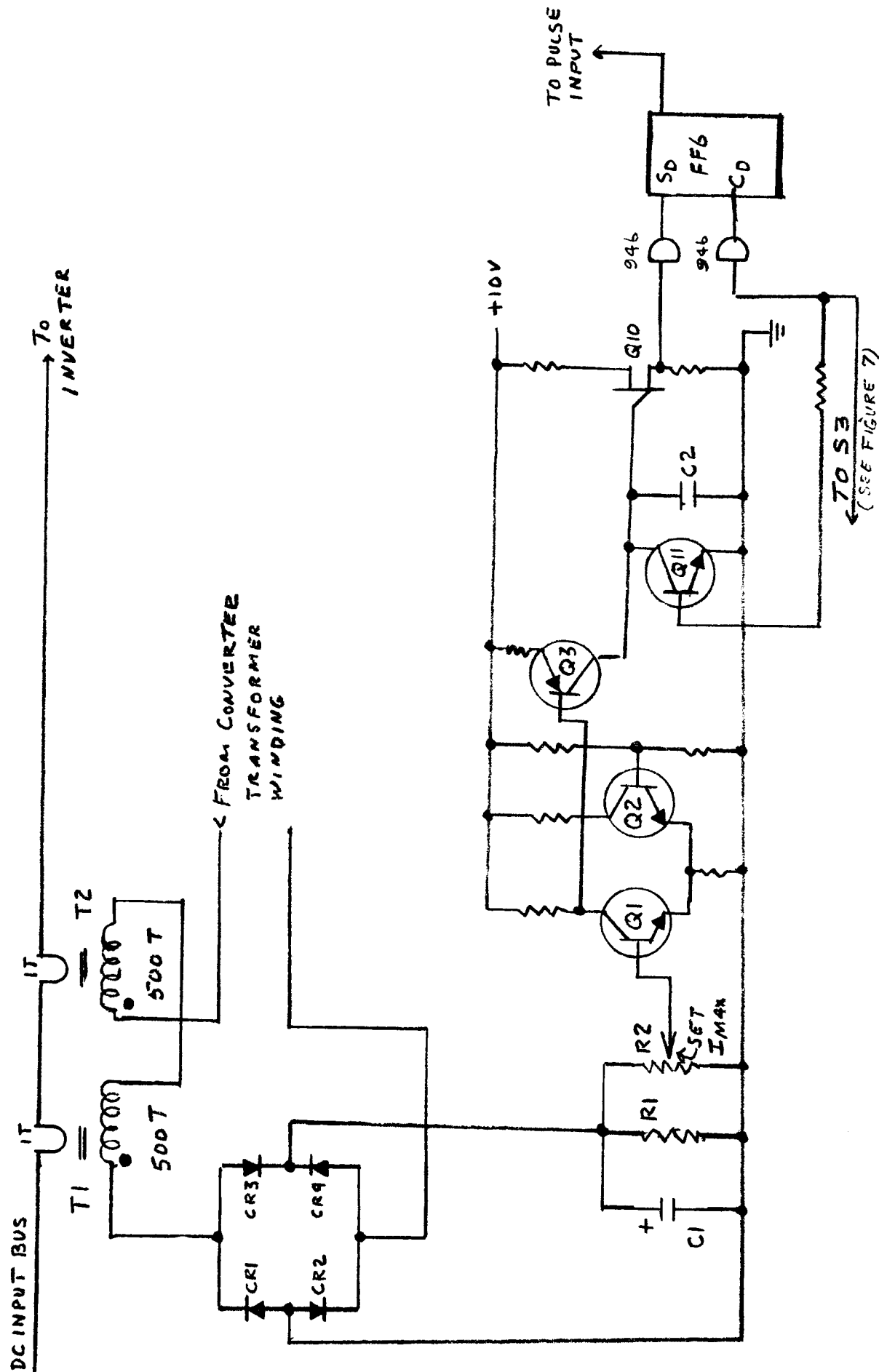


FIGURE 9. TRANSDUCTOR VOLTAGE PULSE WIDTH CONTROL CIRCUIT.

III. WORK PLANNED : NEXT REPORTING PERIOD.

Inverter/motor tests will be conducted to obtain torque/speed curves showing the effect of current limiting. Performance data and the torque/speed curves will be evaluated.